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A model for predicting photovoltaic module performances

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ABSTRACT

The present paper deals with the development of a simulation model for predicting the performances of a solar photovoltaic (PV) system operating under current meteorological conditions at the site location. The proposed model is based on the cell equivalent circuit including a photocurrent source, a diode, a series and shunt resistances. Mathematical expressions developed for modeling the PV generator performances are based on current-voltage characteristic of the considered modules. The developed model allows the prediction of PV cell (module) behavior under different physical and environmental parameters. The model can be extended to extract physical parameters for a given solar PV module as a function of temperature and solar irradiation. A typical 260 W solar panel developed by LG Company was used for model evaluation using Newton-Raphson approach under MATLAB environment in order to analyze its behavior under actual operating conditions. Comparison of our results with data taken from the manufacturer's datasheet shows good agreement and confirms the validity of our model. Hence, the proposed approach can be an alternative to extract different parameters of any PV module to study and predict its performances.

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1. INTRODUCTION

Our environment is facing significant challenges in the present and future decades as energy consumption is expected to globally double during the first half of this century [1]. Due to increasing oil supplies constrains, the world is urged to search for alternative energy sources. Therefore, a better solution would be the investigation in Renewable Energy Sources (RES) [2-4] mainly, solar energy. Solar and other forms of renewable energies are seen as practical and clean solution to meet our planet's growing environmental and energy challenges. In fact, the demand for solar energy is becoming more and more increasing and its consumption more and more generalized. The investigations on solar energy production, utilization and conversion are regularly increasing to cover more fields in the purpose of designing and implementing solar and electrical energy converters of higher performances and efficiency [5].

The most common principle widely known in solar energy conversion is the photovoltaic cell based on a p-n junction as a photodiode, i.e., it generates a voltage across its terminal when a light beam is incident on the device junction area [6]. Designers of electrical converters are interested in modeling PV cell/modules for studying the electrical converters including a PV system. This needs to know how to model the PV device feeding the converter. The PV modules show a nonlinear I-V characteristic with a number of parameters that

need be adjusted during experimental data analysis of practical modules. Mathematical modeling of PV cell/module is important to simulate the PV system and its components.

Different methods for modeling photovoltaic (PV) cell/modules have been developed and explored earlier. Their main difference resides essentially in the electric equivalent circuit of the studied PV cell, their convergence, and complexity. Typically, Townsend [7, 8] model is one of the models developed for evaluating the parameters of the equivalent electric circuit of the cell. However, Rohan. S. Kolkarni and al proposed in their work another method for modeling the solar photovoltaic module using system identification [9]. However, Tarak Salmi and al have proposed a Matlab/Simulink model of PV cell based on mathematical equations using Simulink Bloks [10].

Zaid Hessein Ali et al [11] exposed a Simulation model of solar PV cell and hence PV panel using numerical approach consideraing only the effect of external parameters (temperature and solar irradiance) in western Iraq. The Matlab math modeling is implemented using climate and physical parameters with modeling equations [11, 12]. Newton-Raphson iteration numerical method has been applied to extract the value of current for every working voltage to find P-V curves under the effect of temperature and irradiation of Anbar province West Iraq [11, 13].

In this work, we demonstrate the behavior and functioning of a PV device by exploring its basic equations, modeling and simulating the 260 S1C-G2 PV Module using Newton-Raphson algorithm to solve the nonlinear I-V characteristic under Matlab environment. This is achieved by focusing on both the study of external parameters effects (temperature and irradiance) on the evolution of PV devices performances as well as those of the internal parameters (series resistance and parallel one). Comparison of the obtained data with that of manufacturer's datasheet shows good agreement and confirms the validity of our model.

2. PHOTOVOLTAIC GENERATOR

2.1. Modeling the photovoltaic cell

A solar module is defined as the individual piece of equipment that encompasses numerous solar cells connected in parallel or in series [14]. In order to simulate the real behavior of a photovoltaic cell, an equivalent electric circuit model is needed. Several models are proposed in literature such as the single diode model [15] which is derived from simplifications in the two diode model [16]. A single equivalent circuit model for a PV cell consists of a real diode in parallel with an ideal direct current source as presented in Figure 1.

The two parameters used to model and characterize a PV cell are: the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}). The V_{oc} is the maximum voltage which a solar cell can provide at zero current. The I_{sc} is the maximum current which a solar cell can provide at zero voltage.

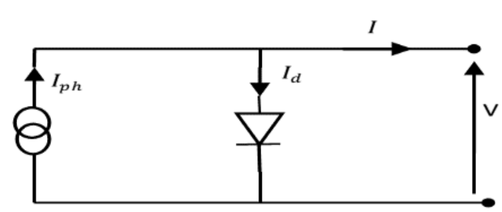

Figure 1. Ideal PV cell model circuit diagram

The output current from the PV cell can be found using the following equation

$$I = I_{ph} - I_d \tag{1}$$

On the other hand, we have

$$I_{sc} = I_{SCTref}\left(1 + a.\left(T_c - T_{ref}\right)\right) \tag{2}$$

I_{sc} at the reference temperature (I_{SCTref}) is found on the datasheet, and a refers to the temperature coefficient of I_{sc} in percent change per degree. The measurements are done under the standard irradiance of 1000 W/m^2 and reference temperature of 25 °C. The photon generated current also varies with respect to the

irradiance G. The assumptions that $I_{sc} \approx I_{ph}$ is generally used since the series resistance (R_s) is low and the parallel resistance R_{sh} is a very high. This leads us to the following expression

$$I_{ph} = \frac{G}{G_{ref}} * I_{SCTref}\left(1 + a.\left(T_c - T_{ref}\right)\right) \quad (3)$$

G : Irradiation at temperature T_c , G_{ref} : Reference irradiance taken equals to standard irradiance of 1000 W/m^2 , T_{ref} Reference temperature equals to 25°C, And (I_d) is the shunted current through the intrinsic diode. Using Shockley's diode model, the diode current can be written

$$I_d = I_0.exp\left\{\left(\frac{\mathrm{V}}{\mathrm{A.K}.T_c/q}\right) - 1\right\} \quad (4)$$

A : Diode quality factor (it is between 1 and 5), K : Boltzmann's constant (1.381.10^{-23} J/K), T_c : Junction temperature in Kelvin, q: Charge of the electron (1.602.10 $^{-19}$ Coulomb), V : Voltage provided by solar cell. I_0 is the diode saturation current, it depends also in temperature as it is expressed in relation (5)

$$I_0 = \frac{I_{scT_c}}{exp\left(\frac{q.V_{ocT_c}}{A.K.T_c}-1\right)}.\left(\frac{T_c}{T_{ref}}\right)^{\frac{3}{\gamma}}.exp\left(\frac{-q.V_{gap}/A.K}{\frac{1}{T_c}-\frac{1}{T_{ref}}}\right) \quad (5)$$

I_{scT_c}: Short-circuit current of the cell at temperature T$_c$, V_{gap} : Energy of the gap (1.16 eV for Silicon).
V_{ocT_c} : Open circuit voltage at temperature T$_c$, T_{ref} : Reference temperature equals to 25°C
γ : Similar to quality factor, it is taken equal to A.

Several cells connected in series form the PV module and a collection of PV modules constitute a PV panel, and finally, the collection of a given number of panels forms the array. The practical current voltage I-V characteristic of a practical module requires the inclusion of the parameters (R_s) and (R_{sh}) which makes the model more accurate as represented in Figure 2.

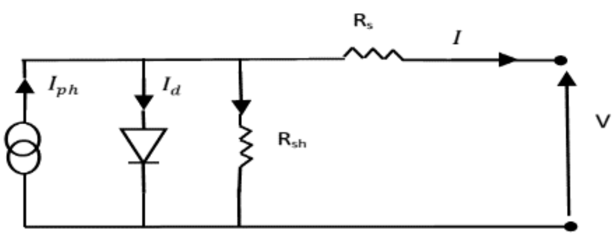

Figure 2. Single diode PV cell model circuit diagram

If we consider $R_{sh} = \infty$, we substitute the (2), (3), (4), (5) and (1) we get:

$$\mathrm{I} = \frac{\mathrm{G}}{\mathrm{G}_{ref}}\ \mathrm{I}_{\mathrm{SCT}_c}\left(1 + \mathrm{a.}\left(\mathrm{T}_c - \mathrm{T}_{ref}\right)\right) - \left[\frac{\mathrm{I}_{\mathrm{scT_c}}}{\exp\left(\frac{\mathrm{q.V_{ocT_c}}}{\mathrm{A.K.T_c}}-1\right)}.\left(\frac{\mathrm{T_c}}{\mathrm{T}_{ref}}\right)^{\frac{3}{\gamma}}.\exp\left(\frac{-\mathrm{q.V_{gap}/A.K}}{\left(\frac{1}{\mathrm{T_c}}-\frac{1}{\mathrm{T}_{ref}}\right)}\right).\exp\left\{\left(\mathrm{q.}\frac{\mathrm{V+R_s.I}}{\mathrm{A.K.T}_c}\right) - 1\right\}\right] \quad (6)$$

Taking into consideration the two parameters R_{sh} and R_s (6) becomes as follow:

$$\mathrm{I} = \frac{\mathrm{G}}{\mathrm{G}_{ref}}.\mathrm{I}_{\mathrm{SCT}_c}.\left(1 + \mathrm{a.}\left(\mathrm{T}_c - \mathrm{T}_{ref}\right)\right) - \left[\frac{\mathrm{I}_{\mathrm{scT_c}}}{\exp\left(\frac{\mathrm{q.V_{ocT_c}}}{\mathrm{A.K.T_c}}-1\right)}.\left(\frac{\mathrm{T_c}}{\mathrm{T}_{ref}}\right)^{\frac{3}{\gamma}}.\exp\left(\frac{-\mathrm{q.}\frac{\mathrm{V_{gap}}}{\mathrm{A.K}}}{\left(\frac{1}{\mathrm{T_c}}-\frac{1}{\mathrm{T}_{ref}}\right)}\right).\exp\left\{\left(\mathrm{q.}\frac{\mathrm{V+R_s.I}}{\mathrm{A.K.T}_c}\right) - 1\right\}\right] - \frac{\mathrm{V+R_s*I}}{\mathrm{R}_{sh}} \quad (7)$$

The series resistance (R_s) accounts for the losses related to the connection of the cells in series, the resistance of the semiconductor material and that of metal grid whereas the parallel one (R_{sh}) accounts for

the losses associated to leakage current through a parallel resistance path to the device. It bcomes considerable for large number of parallel cells. These two parameters could be obtained experimentally from the I-V curve [16, 17]. This method is based on the fact that, the series resistance impacts significantly the I-V curve slope at nearby point $(V_{oc}\ ,0)$ and the parallel one at the point $(0, I_{sc})$, so we can write

$$R_{s0} = -\left.\frac{dV}{dI}\right|_{V=V_{oc}} \quad (8)$$

$$R_{sh0} = -\left.\frac{dV}{dI}\right|_{I=I_{sc}} \quad (9)$$

We have to derive (6) to get (R_s) expression

$$R_s = -\left.\frac{dV}{dI}\right|_{V=V_{oc}} - \frac{1}{\left[\frac{I_{scTc}}{exp\left(\frac{q.V_{ocTc}}{A.K.T_c}-1\right)} \frac{q}{A.K.T_c} exp\left(\frac{q.V_{ocTc}}{A.K.T_c}\right)\right]} \quad (10)$$

This model gives a better precision for many modules. The model expression results from simplifications obtained in the two diode model diagram presented in [16, 18, 19]. Cells connected in series increase the output voltage whereas cells connected in parallel provide higher currents values, so if our module is composed of N_p cells then

$$I_{ph(module)} = I_{ph} * N_p \text{ and } I_{0(module)} = I_0 * N_p$$

The current voltage characteristic of the PV module is a non linear equation; it should be solved using different methods. In this work, we have chosen the Newton-Raphson method for its quick convergence response as indicated in literature [16, 20].

3. NEWTON-RAPHSON METHOD

In this section, it is explained the results of research and at the same time is given the comprehensive discussion. Results can be presented in figures, graphs, tables and others that make the reader understand easily [2, 5]. The discussion can be made in several sub-chapters.
Newton-Raphson algorithm consists in

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (11)$$

f' : is the derivative of the function f
$f(x) = 0$: is the function to be solved,x_n : is the present iteration, andx_{n+1} : is the next iteration
Then our equation to solve would be

$$f(I) = I_{sc} - I - I_0 \exp\left\{\left(q * \frac{V+R_s*I}{A*K*T_c}\right) - 1\right\} - \frac{V+I.R_s}{R_{sh}} = 0 \quad (12)$$

The substitution of (12) in (11) we get

$$I_{n+1} = I_n - \frac{I_{sc} - I_0.exp\left\{\left(q.\frac{V_n + R_s.I_n}{A.K.T_c}\right) - 1\right\} - I_n - \frac{V+I_n.R_s}{R_{sh}}}{-1 - I_0.\left(\left(q.\frac{R_s}{A.K.T_c}\right).exp\left\{\left(q.\frac{V_n + R_s.I_n}{A.K.T_c}\right)\right\}\right) - \frac{R_s}{R_{sh}}} \quad (13)$$

4. RESULTS AND DISCUSSION

In this section, the discussions of the results obtained in this work are divided into five parts. This is because the proposed model has been implemented and simulated under various operating conditions such as varied temperatures, varied irradiances, varying series resistances values and last varying the parallel resistances values. A comparison of obtained results with those taken from the manufacturer's datasheet has been made. According earlier works presented in literature, the purpose of adjusting the mathematical I-V curve at the three perceptible points was successfully achieved. The electrical parameters of LG 260 S1C-G2 PV module data are given in Table 1.

Table 1. LG 260 S1C- G2 PV module specifications under standard test conditions ($1kW/m^2$, Am 1.5, T=25°C)

	Variable	Value
Maximum Power (W)	P_{MAX}	260
Voltage at max power (V)	V_{MPP}	30,1
Current at max power (A)	I_{MPP}	8,64
Open-circuit voltage (V)	V_{OC}	37,3
Short-circuit current (A	I_{SC}	8,94

4.1. Impact of irradiation

Simulations are made at constant temperature of 25°C for various irradiations: (200, 400, 600, 800 and 1000 W/m^2), the Current Voltage and Power Voltage curves obtained are shown in Figure 4. From the results shown in Figure 4, it is obvious that the current module is directly proportional to irradiance as the photo current is directly proportional to irradiance and demonstrated in (3). It can be noticed that as irradiance value decreases, short-circuit current decreases proportionally. Decreasing irradiance also reduces the open circuit voltage (V_{oc}), but following a logarithmic relationship leading relatively to a modest change at (V_{oc}). Results illustrated in Figure 5 show that the module maximum power is also directly proportional to irradiance which makes the module as being more efficient when irradiance is important.

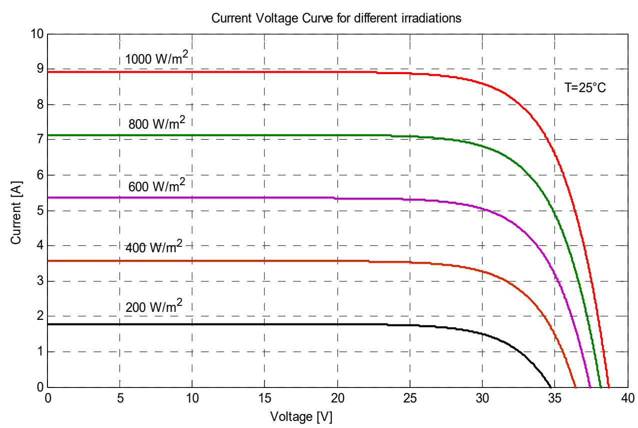

Figure 4. Irradiation level impact on current-voltage curves

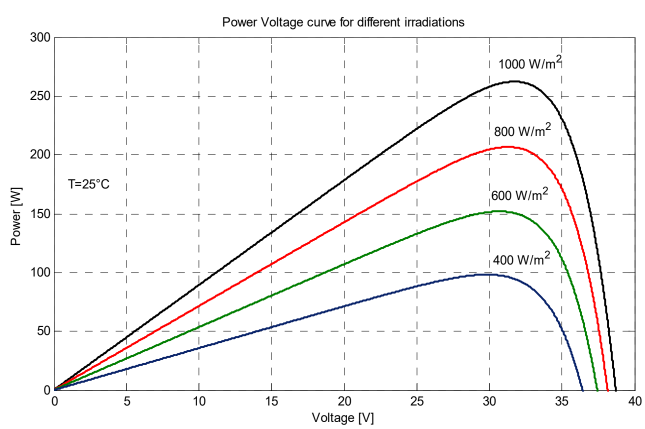

Figure 5. Irradiation level impact on power-voltage curves

4.2. Impact of temperature

Simulations are made at constant irradiance of 1000 W/m^2 for various temperatures: (0, 25, 50 and 75°C), the Current Voltage and Power Voltage curves obtained are presented in Figure 6 and Figure 7. As can be seen in Figure 6, increasing module's temperature decreases significantly the open-circuit voltage while the short- circuit current increases only slightly. In Figure 8, it can also be noticed that when the temperature of the module increases the power produced decreases, affecting negatively the module efficiency.

The effect of temperature appears in the decrease of the open circuit voltage value. We conclude that maximum power generated by the PV generator depends strongly on the solar irradiation and temperature which means that the solar module generates a maximum power only for certain value of current and corresponding voltage.

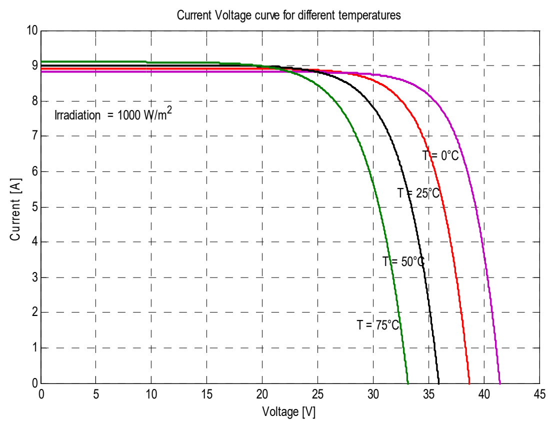

Figure 6. Temperature impact on current-voltage curves

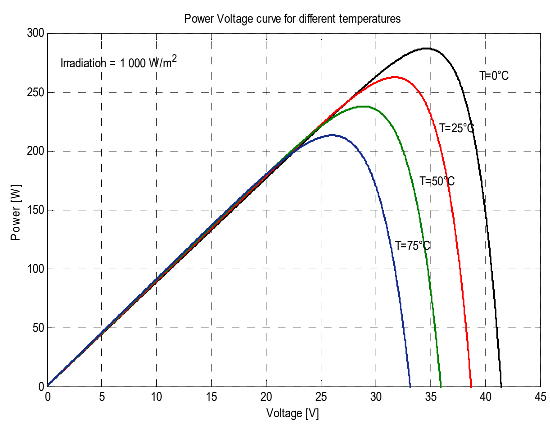

Figure 7. Temperature impact on power-voltage curves

4.3. Impact of series resistance

Figure 8 and Figure 9 show the simulation results of current-voltage and power-voltage curves obtained under the same Standard Test Conditions of temperature and irradiation for different series resistance values (R_s).

As seen in Figure 8, the series resistance of the module has a noticeable impact of the current-voltage curve slope in the region where the cell operates as a voltage generator. Integrating the series resistance effect in the PV equivalent circuit results in a voltage decrease at any given current. The increase in the series resistance value has a negative impact on the maximum power generated and hence, the efficiency decreases as illustrated in Figure 9.

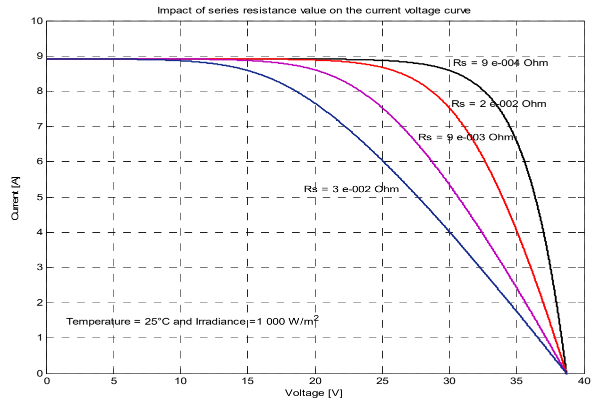

Figure 8. Series resistance impact on current-voltage curves

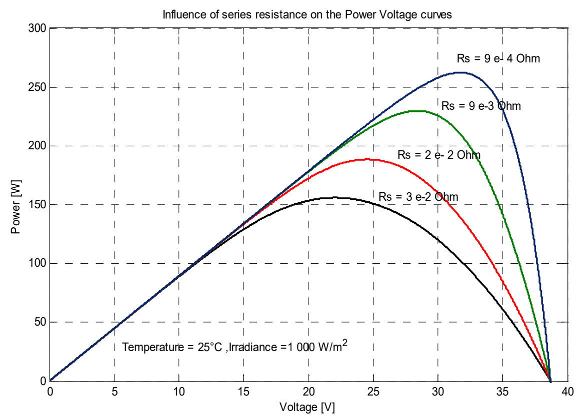

Figure 9. Series Resistance Impact Power-Voltage Curves

4.4. Impact of shunt resistance

Simulations are made for Standard Test Conditions of temperature and irradiation (T=25°C and G=1000W/m^2). The equivalent electric circuit of a single diode model considered in this work is the one presented in Figure 2 considering $R_s = 8{,}9006.10^{-4}$ Ohm.

Figure 11 and Figure 12 show the simulation results of current-voltage and power-voltage curves characteristic found under the same standard test conditions of temperature and irradiation and for different values of parallel resistance (R_{sh}). Figure 10 shows that the parallel resistance of the module has a great impact on the current-voltage curve slope in the region where the cell operates as a current generator.

The increase in the parallel resistance value causes the increase in the value of the maximum power generated so the efficiency rises as demonstrated in the Figure 11. The shunt resistance serves as alternative paths for the free carriers produced by solar radiation. A higher shunt resistance means that a large amount of these carriers contribute to generate power whereas a lower shunt resistance indicates large losses, affecting mainly the slope of the I–V curve on the proximity of the short circuit region [21, 22]. The cell efficiency is affected because shunts reduce the Fill Factor (FF) and the Open Circuit Voltage (V_{oc}). This effect becomes more prominant under low light conditions [23]. A low shunt resistance can lead to hot-spots in reverse cells, especially when the power dissipation occurs in a small area [24].

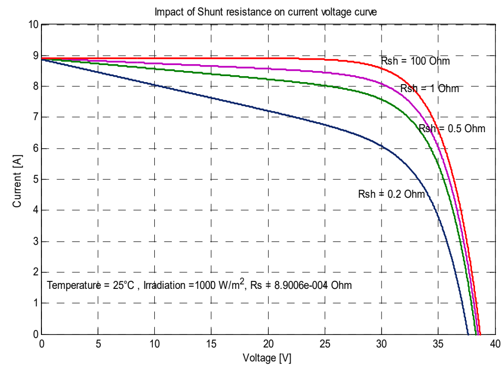

Figure 10. Parallel resistance impact on current-voltage curves

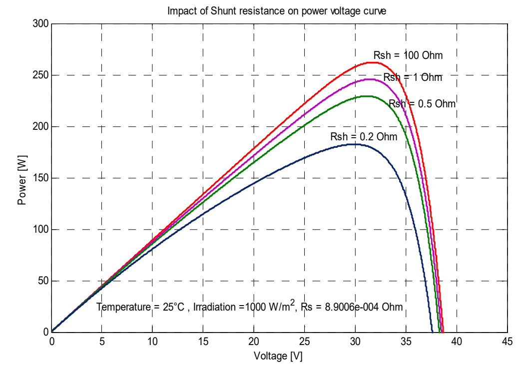

Figure 11. Parallel resistance impact on power-voltage curves

4.5. Comparison of results with the results taken from manufacturer's datasheet and previous works modelling

A comparison between calculated and experimental values of the considered PV module is made. The obtained results are presented in Figure 12.

Results presented in Figure 12 shows consistencies between experimental and predicted results. It comes out evident that the calculated results are in good agreement with the experimental data provided by the manufacturer in datasheet. According to previous works presented in literature [10, 11, 15], the purpose of adjusting the mathematical I-V curve at the three perceptible points (Short Circuit Current, Open Circuit Voltage and Maximum Power) was successfully achieved.

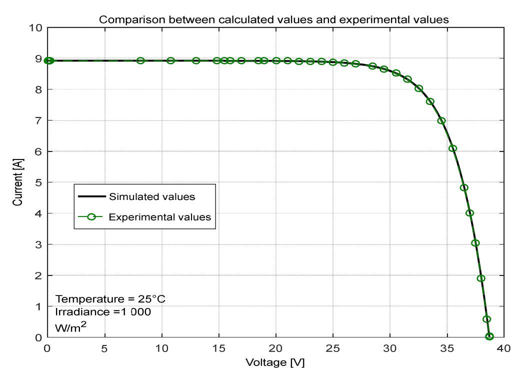

Figure 12. Experimental and calculated I-V curves of the LG 260 S1C-G2 PV module under standard test conditions (25°C, 1000 W/m^2 and AM 1.5)

5. CONCLUSION

The represents work achieved a contribution to the prediction of photovoltaic device performances which constitute a very important step in the study of any PV system. The simplicity of a single diode model with the technique of adjusting the parameters and the improvements proposed in this paper can make this model an alternative tool for designers who are in need of a simple and effective model for simulating PV devices associated to power converters. So, the modeling simulation by Matlab is helful for PV systems designers due to the simplicity, effectiveness, accuracy and easy to use simulation and modeling method.

The proposed model was used to study the impact of series and parallel resistances as well as temperature and irradiation on the development of photovoltaic device performances in terms of reliability and efficiency. Furthermore, simulation results show an excellent agreement with the experimental data taken directly from the manufacturer datasheet. Finaly our contribution could constitute a first step to build up a full solar PV power electronic conversion system in developing a grid connected application.

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